Beam Instrumentation for X-ray FELs

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Outline

- X-ray FEL overview
- Diagnostics requirements for X-ray FELs
- Transverse Diagnostics
- Longitudinal Diagnostics
- Summary
X-ray FEL Overview

<table>
<thead>
<tr>
<th>Energy</th>
<th>Wave length</th>
<th>Bunch Charge</th>
<th>Peak Curr.</th>
<th>Emittance</th>
<th>Gain length</th>
<th>Und. length</th>
<th>Rate (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>13.6</td>
<td>1.5 Å</td>
<td>0.02-1nC</td>
<td>3kA</td>
<td>.2-1 μm</td>
<td>3.5 m</td>
<td>100m</td>
<td>120</td>
</tr>
<tr>
<td>8</td>
<td>1 Å</td>
<td>0.2nC</td>
<td>4kA</td>
<td>.7 μm</td>
<td>~10 m</td>
<td>100m</td>
<td>60</td>
</tr>
<tr>
<td>17.5</td>
<td>1 Å</td>
<td>0.1-1nC</td>
<td>5kA</td>
<td>1-2 μm</td>
<td>3.7 m</td>
<td>130m</td>
<td>10/5E6</td>
</tr>
</tbody>
</table>
X-Ray FEL Diagnostics Requirements

- Work from MeV to GeV range, 10s of pC to nC

- **Transverse**
  - Typical $\beta \sim 10 - 100$ m, $\varepsilon_n \sim 1$ $\mu$m, beam size 10s $\mu$m
  - Need $\sim 10$ $\mu$m resolution for beam profiles
  - Beam position $x < \sigma/10$ for stable photon beam
  - Need few $\mu$m BPM resolution
  - Straight beam orbit in undulator within few $\mu$m
  - Need sub-$\mu$m cavity BPM

- **Longitudinal**
  - Typical $10^{-4}$ FEL bandwidth, energy resolution $\ll 10^{-4}$
  - Need $\sim 10$ $\mu$m energy BPM resolution for $\sim 10$ cm dispersion
  - Bunch lengths 10s fs
  - Need timing and length resolution of few fs

- Non-intercepting/intra-bunch resolution for feedback systems
~70 BPMs, strip line
- 10 µm resolution
- Few button, cavity
- Electronics for 0.5 – 1 nC
- Upgrade to 50 pC beam

E-XFEL BPM development
- Cavity BPM at 3.3 GHz
- 1 µm resolution
- Low Q to resolve intra-bunch train position
- Upgrade plan for FLASH undulator BPMs
Dipole mode cavity at 4.76 GHz + monopole cavity
Shifted from main RF frequency to avoid dark current
Measurements at SCSS test accelerator
Position resolution < 200 nm
Timing resolution from TM\textsubscript{010} cavity < 25 fs

Matsubara, IPAC 2010, MOPE004

H. Maesaka et al., DIPAC09, MOPD07
LCLS Beam Position Monitors

- 145 strip line type
  - Charge range ~10 pC to few nC with variable attenuators
  - Continuous calibration with test pulse between beam triggers
  - 3 μm resolution (25 μm at 20 pC)

- 35 cavity type between undulators
  - Dipole/monopole cavity at 11.4 GHz
  - < 300 nm resolution (2 μm at 20 pC)
  - Bi-weekly calibrate with girder motion & beam based alignment

Strip Line Electronics

E. Medvedko et al., BIW 2008, TUPTPF037
YAG Screens
- Powder or crystal
- Saturate ~nC/mm²
- High sensitivity

OTR Screens
- Thin Al foil or Si wafer
- Better resolution

FLASH
- 20 OTR with up to 10 μm resolution
- Matching into BCs & undulator
- COTR at high compression

LCLS
- 20 YAG & OTR, 50 – 10 μm resolution
- Gun commissioning, injector tune-up
LCLS OTR Screens

- Injector diagnostics
- Emittance of 10 slices at 20 pC
- COTR prevents use beyond injector
- Main dump OTR replaced with YAG

Also see S. Wesch & B. Schmidt, WEOA01
Multi shot method
- Intercept beam with thin wire
- Use beam loss monitors to measure charge profile

FLASH wire scanners
- Agree well with OTR screens
- Seldom used, slow scan at 10 Hz

E-XFEL development
- Scan with 1 m/s within bunch train

LCLS wire scanners
- Main method past injector (COTR)
- Need to correct for beam jitter
- Synchronous acquisition of beam orbit, wire position and PMT signal

Wire Scanners

xmean = 0.12 ± 0.01 mm
xrms = 41.9 ± 4.40 μm

xmean = 0.11 ± 0.00 mm
xrms = 30.8 ± 0.63 μm

Courtesy A. Brenger
Transverse Deflecting Cavity

- Impose time dependent transverse kick on beam
- Phase advance 90° to screen
- Time calibration with phase scan

LCLS Laser Heater

energy

Laser: 40 µJ

σ_E ≈ 45 keV, σ_z ≈ 2.5 ps

Dipole magnet

RF

'Streak'

S-band

Δψ ≈ 90°

β_d

β_s

2.44 m

3 wires
3 OTR

DL1

135 MeV

L1S

L0

TCAV0

L1X

gun

heater

H. Edwards et al., LINAC10, MO304

Overlaid single shot images of two bunches streaked with LOLA

3.9 GHz off

3.9 GHz on

FLASH TDC
**FLASH**
- Resolution 20 fs temporal, $1.4 \cdot 10^{-4}$ energy
- Single bunch kicker
- Straight ahead screen impeded by COTR
- Mostly screen in spectrometer used

**LCLS**
- Wire scanner instead of OTR
- Jitter correction imperative
- Shortest bunches ~10 fs

![Correlation Plot 22-Nov-2009 14:27:54](WIRE:LI28:144:BLEN)

![Bunch length (um) vs. L2 chirp voltage (MeV)](LCLS.png)

Courtesy C. Behrens

36 fs rms
LCLS X-Band Transverse Deflector

- Planned after LCLS undulator
- Compared to S-Band Deflector
  - 4x frequency (11.424 GHz)
  - 2x voltage (43 MV)
  - 8x more kick
- Calibration factor of ~100 feasible
- Longitudinal phase space on main dump screen
- Obtain e-beam current profile
- Get x-ray pulse length from induced energy loss

X-band, 11.4GHz

Traveling Wave, length ~60 cm
(Courtesy of V. Dolgashev)

Compared to S-Band Deflector

- 4x frequency (11.424 GHz)
- 2x voltage (43 MV)
- 8x more kick

Calibration factor of ~100 feasible

Longitudinal phase space on main dump screen

Obtain e-beam current profile

Get x-ray pulse length from induced energy loss

Courtesy Y. Ding
Coherent diffraction radiation detector
Radiator is slit metal screen
Optical radiation transport with GHz to THz bandwidth
Signal from pyroelectric detector
Fast detection resolves bunch train
Slow & fast phase feedback for upstream accelerator structures

C. Behrens et al., IPAC10, MOPD090

F. Löhl et al., PRL 104 (2010) 144801
Coherent edge radiation from last chicane bend
- Installed at BC1 & BC2
- BLM provides only signal related to bunch length
- Absolute measurement with transverse deflecting cavity for calibration
- Noise better than 3%

Empirical fit of signal to \((\sigma_z)^{-4/3}\)
- Calculate peak current for 120 Hz fast feedback system
- Regulate upstream linac phases
FLASH grating spectrometer
- Wavelength range 3 – 65 μm with multiple gratings
- Bunch features of 15 fs resolved

LCLS Prism spectrometer
- From 0.8 – 39 μm with KRS-5 prism
- Suitable for ≥1 μm bunch length

**Grating Spectrometer**

B. Schmidt et al., EPAC08, MOPC029

**Pyro-Array**

Pyreos Ltd, Edinburgh, UK

**Prism Spectrometer**

See C. Behrens et al., TUPD38

**LCLS Form Factor 20 pC**
Beam signal from 4 button pick-up
Laser clock with 6 fs stability
Electro-optic modulator encodes beam signal on laser amplitude
Fast sampling for intra-bunch train feedback
5 BAM installed with 5 fs resolution

FPGA based controller board
PID controller for amplitude correction from BAM signal
Latency of 30 μs due to SC RF
Monopole mode cavity at 2805 MHz
Down-mix with S-band 2856 MHz
Beam jitter measured 50 fs rms
Jitter between two cavities 15 fs

Phase Cavity

2805 MHz

Adjustable Attenuator

Mixer

2856 MHz

Trigger

16 Bit Digitizer

1/4 Divider

Phase Measurement Software

X6 Multiplier

2856 MHz

119 MHz

Timing signals for user experiments
Offline data analysis
Synchronize lasers

J. Frisch et al., IPAC10, TUPE066

Jitter measurement 50 fs rms
Jitter between two cavities 15 fs

Synchronization of lasers

Reference signals

476 MHz Reference

J. Frisch et al., IPAC10, TUPE066
- Energy measurement with $< 10^{-4}$ resolution
- ICCD for energy spread of single bunch
- Multi-anode PMT for centroid of bunch train
- 14-bit ADC at 1 MHz for bunch train resolution
- IBFB with a learning FF algorithm

A. Wilhelm et al., DIPAC09, TUPD43

C. Gerth et al., DIPAC09, TUPD22
Accelerator Configuration Change

- LCLS users request frequent energy changes
- Stable transverse & longitudinal feedbacks
- High level applications to integrate various diagnostics, feedback systems & controls
- Automatic energy change from 12 – 14.5 GeV with only 30% X-ray energy loss

N. Lipkowitz et al., PAC11, WEOBS4
Diagnostics meets requirements to adequately measure beam parameters needed for X-FELs.

Reliable diagnostics available for daily operation of machine.

Commissioning tasks require more specialized diagnostics used by experts.

Issue is 2D spatial diagnostics for ultra-bright beams (COTR).

Challenging task remains to measure <10 fs bunch lengths.
Thanks to N. Baboi, C. Behrens, K. Honkavaara & S. Schreiber at FLASH for lots of helpful information

Thanks to Y. Ding, J. Frisch and everyone else at LCLS